



Quantum Acoustic Devices for Low-Threshold Dark Matter Detection

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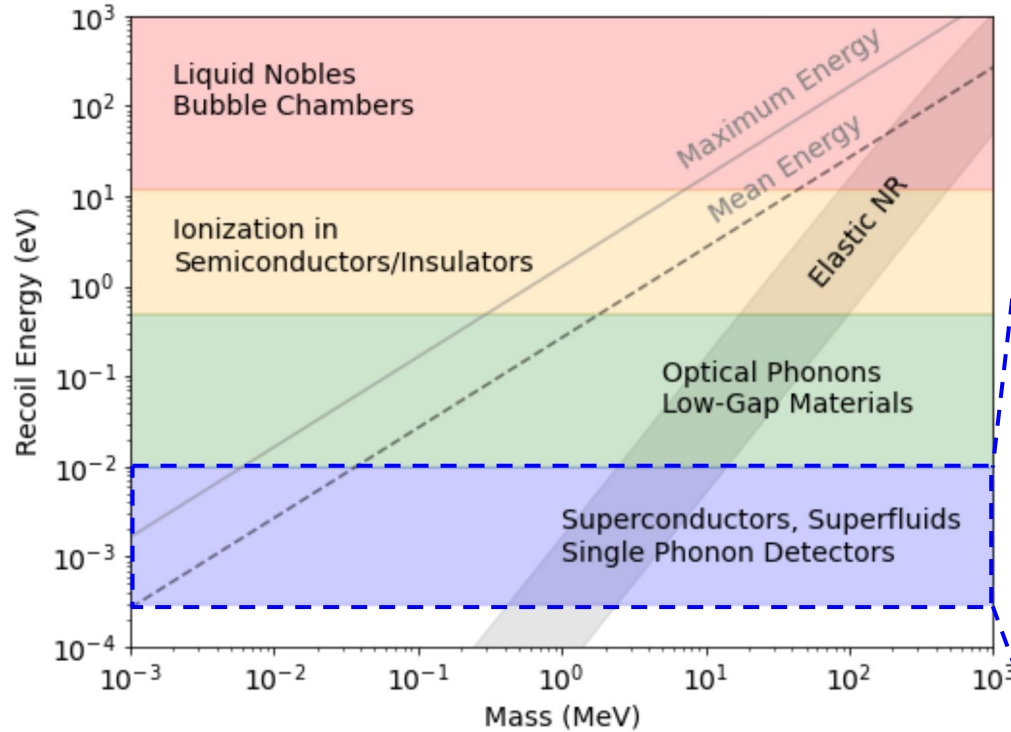
CPAD 2024

11/21/2024

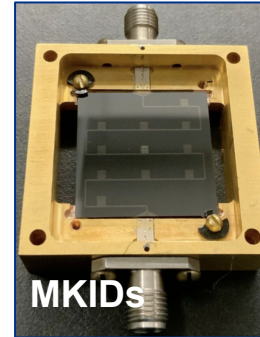
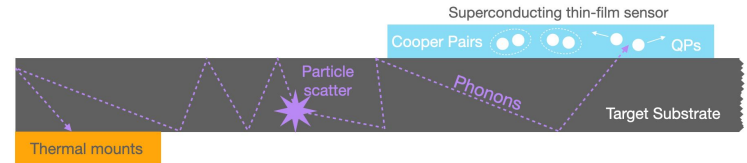


Low Thresholds for Dark Matter Sensing

Sensitivity to lower-mass ($< \text{GeV}$) dark matter puts strong emphasis on lowering detector energy threshold.



Athermal phonon sensing in superconductors:
low threshold from small Δ needed to break Cooper pair into 2 quasiparticles (QPs)



<https://doi.org/10.1103/PhysRevApplied.22.044045>

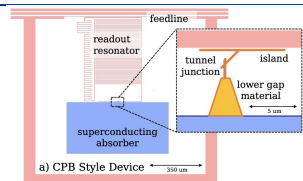


<https://doi.org/10.1063/5.0032372>

Superconducting Qubit Athermal Phonon Sensors

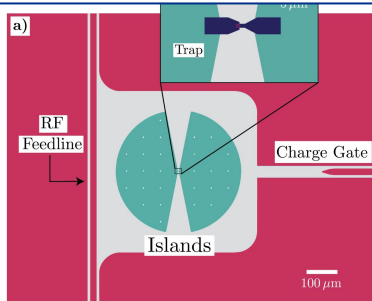
Some pairbreaking sensor architectures derive inspiration from design of superconducting qubits used in the field of quantum computing.

QPD Sensor Design



<https://arxiv.org/pdf/2405.17192>

SQuAT Sensor Design



<https://arxiv.org/abs/2310.01345>

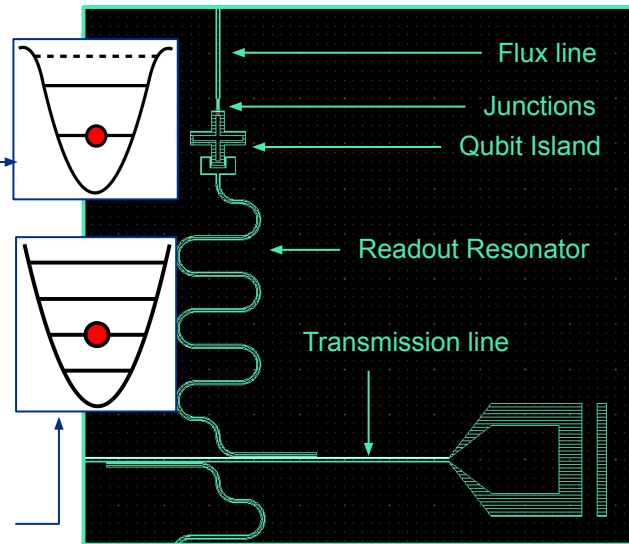
Superconducting Qubits for Quantum Computing

SC Qubit:

- Anharmonic LC oscillator
- Bottom two energy states ($|g\rangle, |e\rangle$) form qu-“bit”
- T_1 coherence times: 10-1000 μ s

Control

- GHz-scale transition freq.
- Microwave/RF control
- Qubit frequency tunable!
- Read out through EM resonator/cavity



Resonant Energy Exchange in Qubits

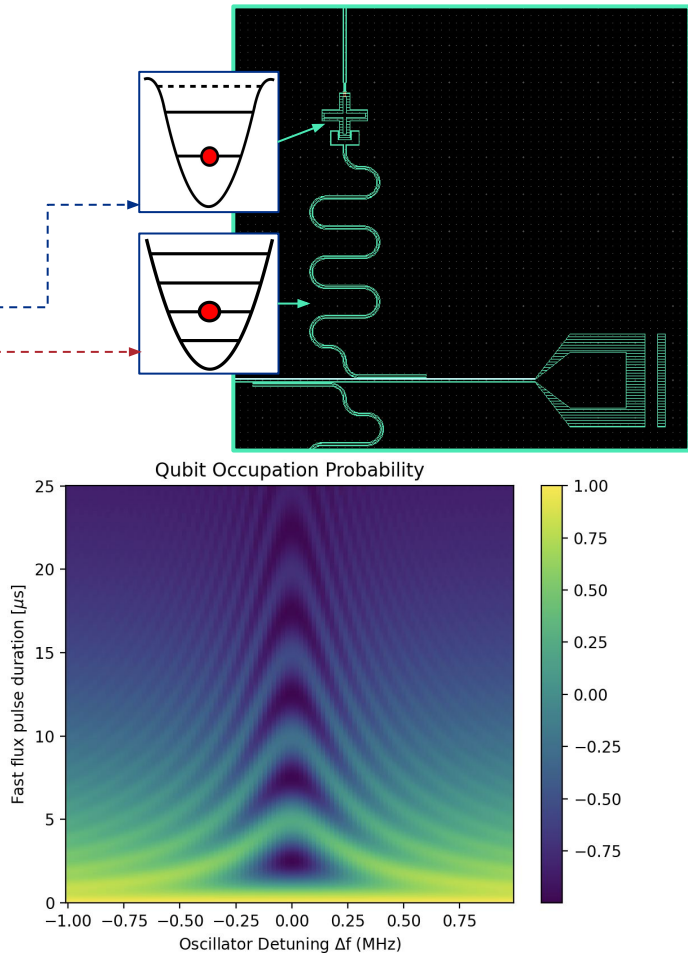
Useful tool for QIS devices: resonant energy exchange (Rabi Oscillations) between coupled oscillators.

Hamiltonian of two quantum oscillators “a” and “b” coupled with strength g :

$$H = \omega_q a^\dagger a + \omega_n b^\dagger b + g (a^\dagger b + ab^\dagger)$$

Oscillator “a” energy Oscillator “b” energy Transfer excitation: $b \rightarrow a$ Transfer excitation: $a \rightarrow b$

When the oscillators’ frequencies are brought on resonance, the total system evolves by swapping an excitation from one oscillator to the other.



Quantum Acoustics

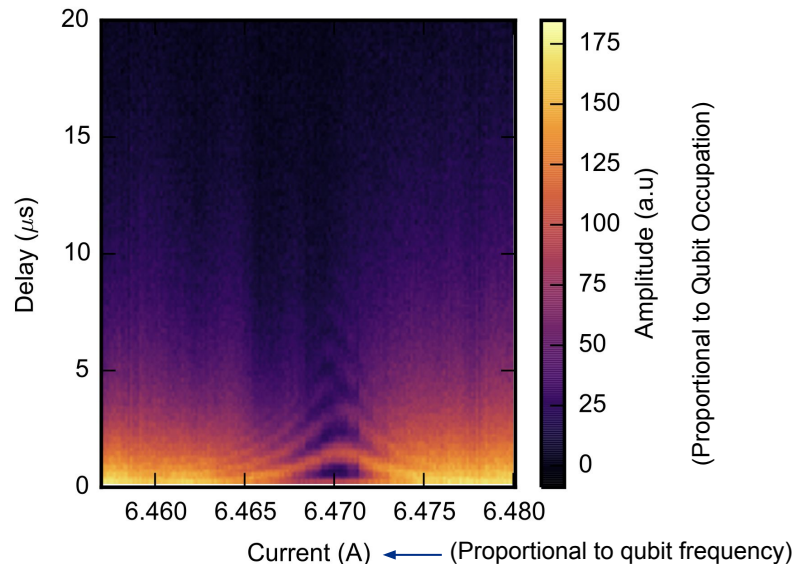
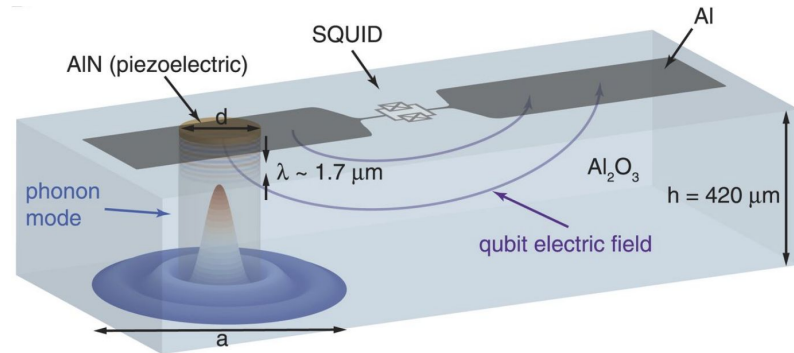
As long as you can physically achieve the coupling g , can generalize resonant exchange to other systems.

Quantum acoustics: piezoelectric coupling between high-overtone bulk acoustic resonator (hBAR) and superconducting qubits.

$$H = \omega_q a^\dagger a + \omega_n b^\dagger b + g(a^\dagger b + ab^\dagger)$$

↑ SC Qubit ↑ Acoustic cavity (hBAR) ↑ Piezoelectric coupling term

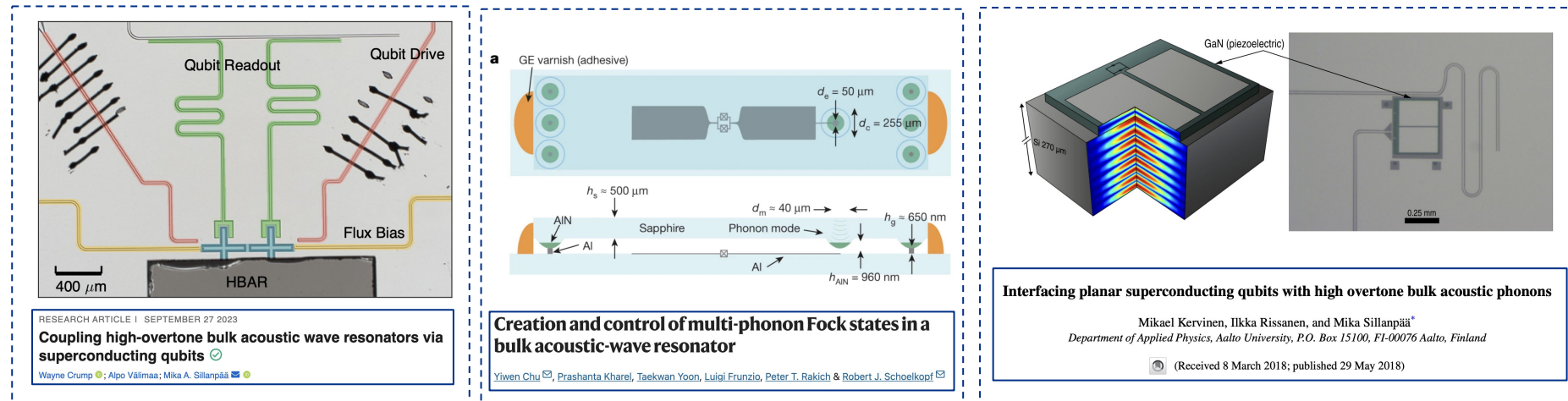
Single-quanta energy exchange has been achieved between a qubit mode and an acoustic standing wave at few-GHz frequencies ($\sim 10\mu\text{eV}$)



<https://www.science.org/doi/10.1126/science.aao1511>

Quantum Acoustics Devices in the Field

Quantum acoustics systems have been commonly achieved in recent years using a variety of different designs for a variety of QIS applications:



...and lots more!

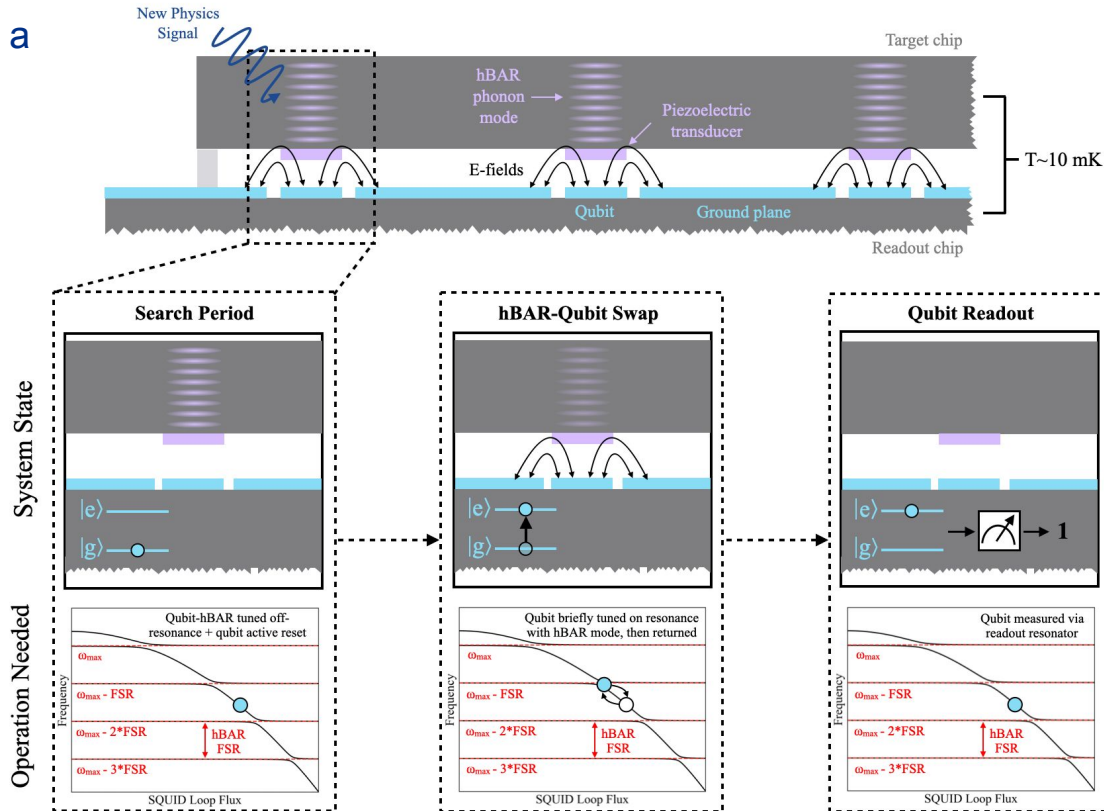
If we can *control* single phonons at the 10 μeV scale, we should be able to *sense* environmental phonons at the same energy scale with the same technology.

The Qubit-Coupled hBAR as a Detector

Goal: develop the qubit-coupled hBAR as a *detector* for single $10\ \mu\text{eV}$ -scale phonons using resonant energy exchange.

“Phonon counting” technique:

1. Reset qubit to ground state
2. Wait “search time” Δt for phonon to “arrive” in hBAR
3. Trigger resonant “swap”
4. Read out qubit state

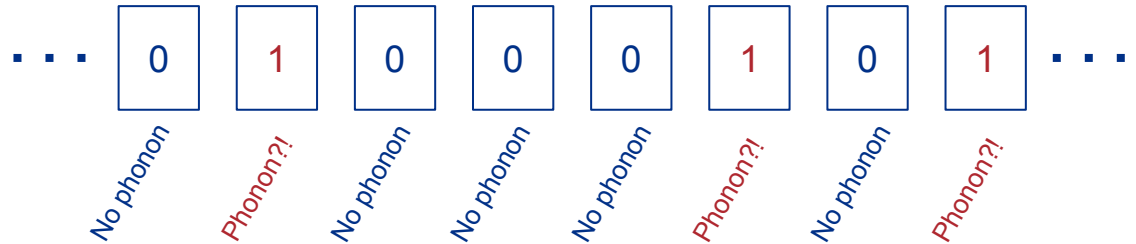
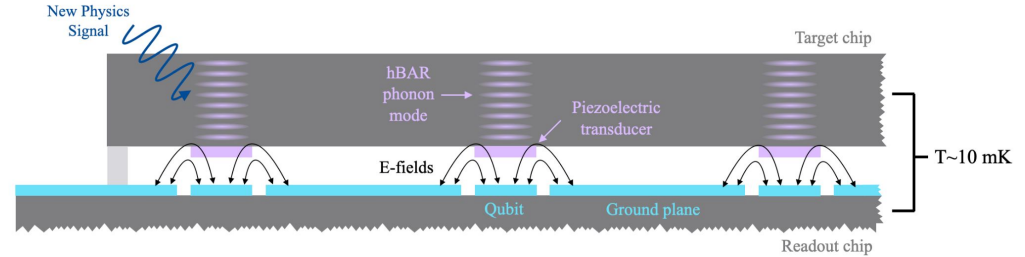


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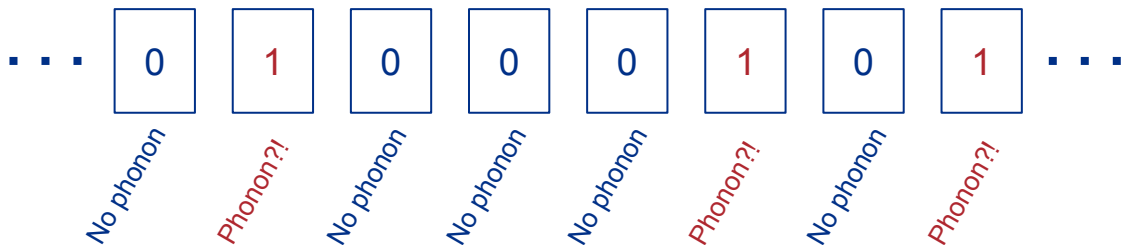
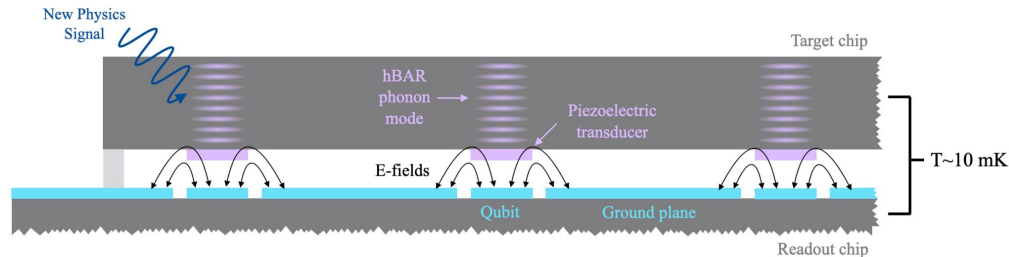
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5. Repeat *ad nauseum*

How sensitive can this be? Need:

- “Swap” efficiency
- Dark count backgrounds

Recent paper:

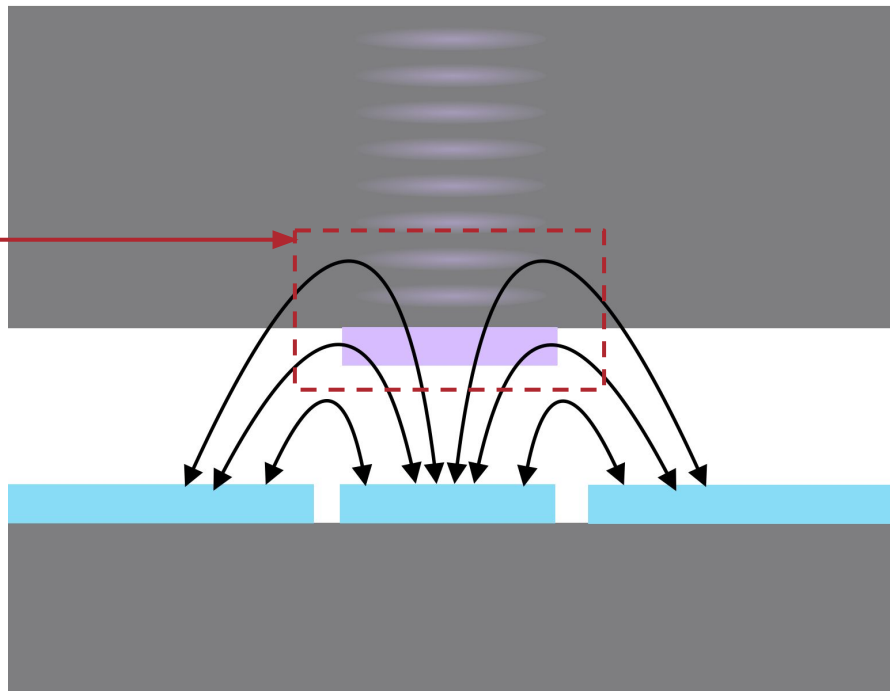
<https://arxiv.org/pdf/2410.17308>



Swap Efficiency

To understand swap efficiency, need to understand:

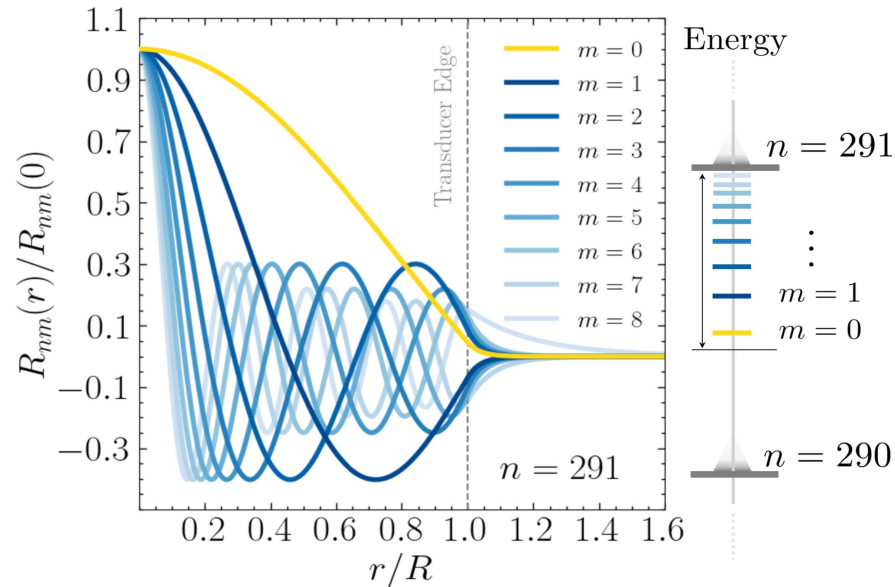
1. Coupling: How well-matched is the phonon standing mode to the strain produced from the qubit E-field + piezo? 
2. How the phonon mode + qubit system evolves in time.



Efficiency: hBAR Phonon Modes

For a given longitudinal mode, the hBAR has a rich set of *radial* “*m*” phonon modes with different frequencies and varying hBAR-qubit coupling strengths.

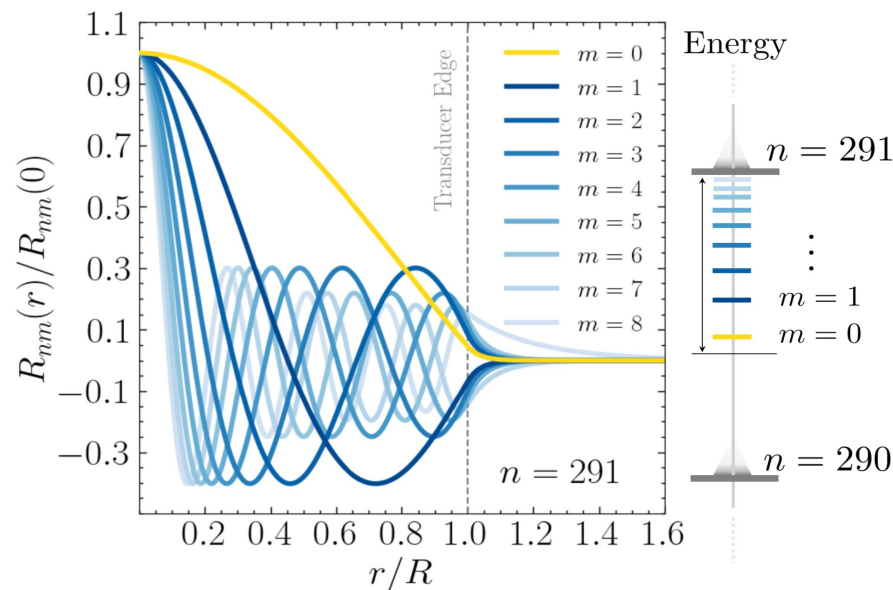
$$U_{nm}(r, z) = \cos\left(\frac{n\pi z}{L + h(r)}\right) R_{nm}(r)$$



Efficiency: hBAR Phonon Modes

For a given longitudinal mode, the hBAR has a rich set of *radial* “m” phonon modes with different frequencies and varying hBAR-qubit coupling strengths.

$$U_{nm}(r, z) = \cos\left(\frac{n\pi z}{L + h(r)}\right) R_{nm}(r)$$



Let's look back at our qubit-hBAR hamiltonian...

$$H = \omega_q a^\dagger a + \omega_n b^\dagger b + g(a^\dagger b + ab^\dagger)$$

More realistically:

$$\sum_{nm} g_{nm} (a^\dagger b_{nm} + b_{nm}^\dagger a)$$

Couplings g_{nm} scale inversely with radial mode number:

$$g_{nm} = e_{\text{pt}} E_q \sqrt{\frac{2\pi R^2}{\rho_h \omega_{nm} L}} \mathcal{B}_{nm}$$

Efficiency: Phonon Mode Evolution

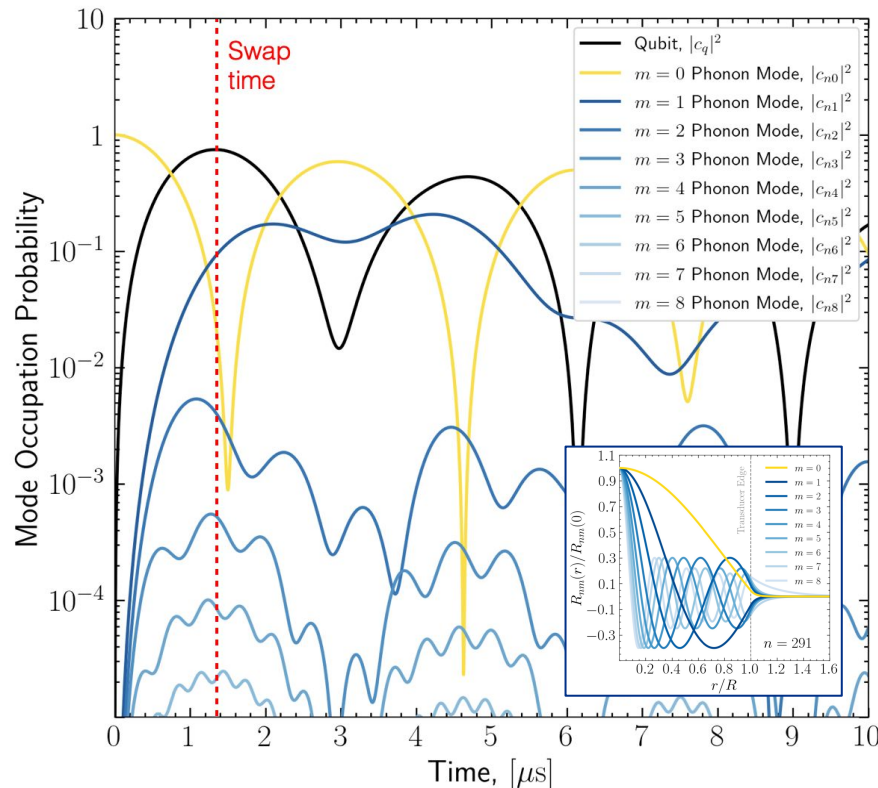
Even if only one phonon mode is initially occupied, the qubit actually evolves with **all** of these coupled modes.

- More modes $\rightarrow$ more ways to “split” signal $\rightarrow$ small reduction in swap efficiency

For a phonon starting in the $m=0$ mode, **swap efficiency is of order unity (~70%)**

Other effects

- Longer qubit $T_1 \rightarrow$ higher efficiency
- Larger $g_{mn} \rightarrow$ higher efficiency



Dark Count Backgrounds

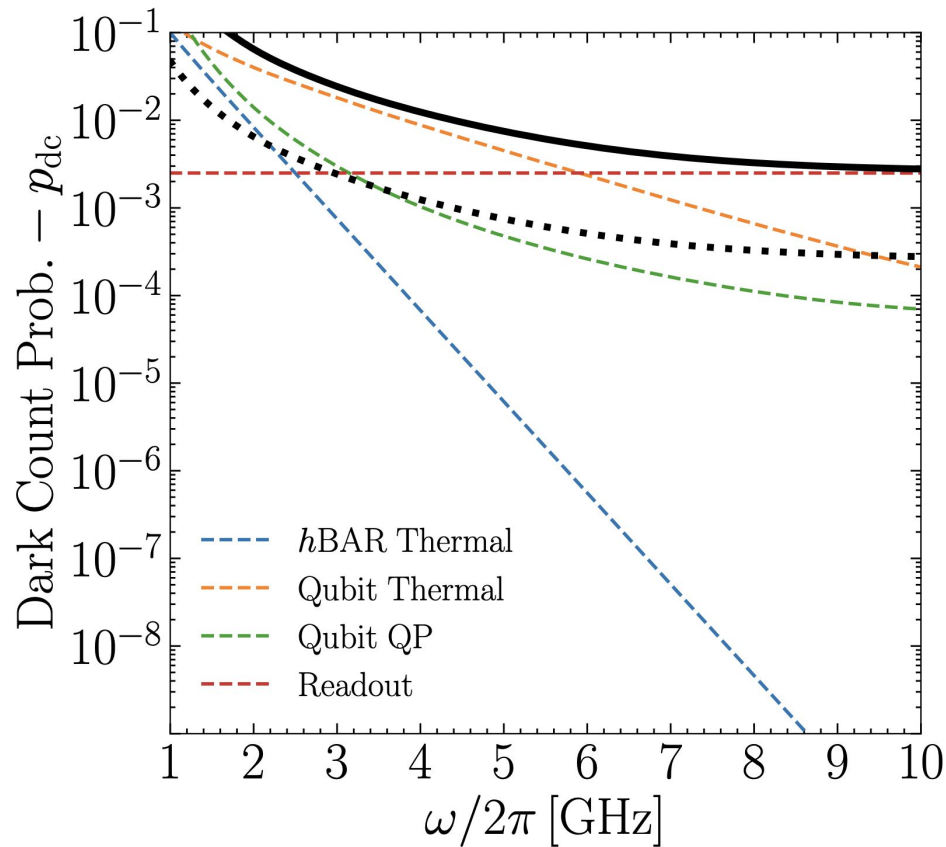
“Dark count” backgrounds in this sensing scheme are currently driven by spurious qubit excitation and readout fidelity.

Spurious qubit excitation: “real” background

- Excitation via “hot” nonequilibrium QPs
- “Thermal” excitation from non-QP bath:

$$p_{\text{th},q} \approx \left[\frac{\Delta t \omega_q}{2Q_q} \frac{1}{e^{\omega_q/T_q^{\text{eff}}} - 1} \right] \left[1 + e^{-T_m \omega_{nm}/Q_p} \right]$$

Readout fidelity: misread $|g\rangle$ as $|e\rangle$ during state readout.



“How do the phonons get there?” Wavelike BSM Projections

This qubit-coupled hBAR gives us the ability to probe “wavelike” BSM physics.

Searches for “effective force” BSM physics:

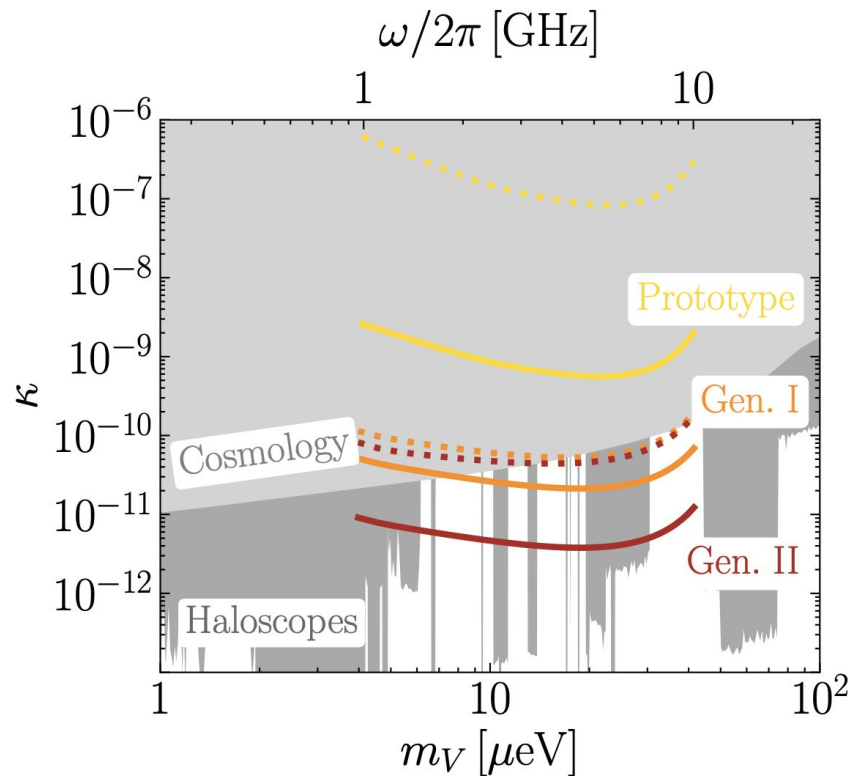
$$|\langle nm | \delta H_0 | 0 \rangle|^2 = \left(\frac{f_0}{\rho_h} \right)^2 \frac{2}{\omega_{nm}} \frac{M_\lambda^2}{M_h} c_{nm}^2$$

Dark photon:

- Couples to and drives piezo transducer
- Potential daily modulation from preferred polarization

High-frequency gravitational waves

- Couples to entire hBAR



“How do the phonons get there?” Particle Scatters

This qubit-coupled hBAR may also give us the ability to probe particle impacts at low threshold.

Good news: plenty of phonons produced in particle impacts!

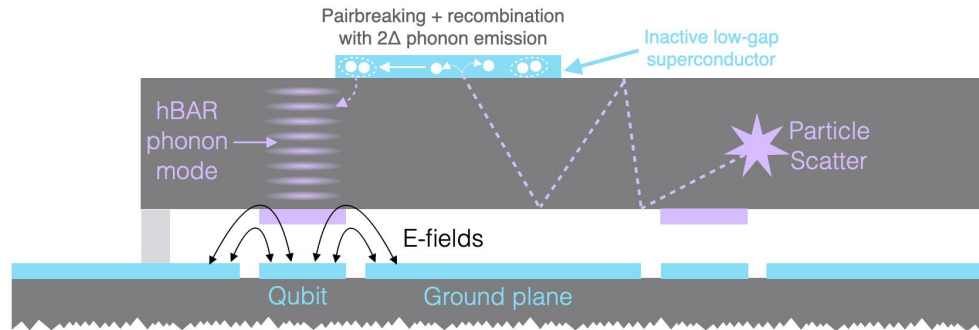
Bad news: in most cases, phonons produced have *too much* energy to be sensed by the hBAR.

- Particle scatters $\rightarrow$ meV-scale
- hBAR $\rightarrow$ 10 μ eV-scale

Need a way to *downconvert* phonons.

- Bulk downconversion too slow!
- Normal metal downconversion: 
- Superconductor gap-edge downconversion + recombination at 2Δ 

Experimental campaigns planned to understand feasibility of this strategy.



Phonon downconversion to suppress correlated errors in superconducting qubits

[V. Jaia](#), [J. Ku](#), [A. Ballard](#), [C. P. Larson](#), [E. Yelton](#), [C. H. Liu](#), [S. Patel](#), [R. McDermott](#) & [B. L. T. Plourde](#) 

Material	Hf	α -W	α -W + β -W
Gap, 2Δ	30 μ eV	3 μ eV	O(10 μ eV), tunable

The Campaigns Ahead

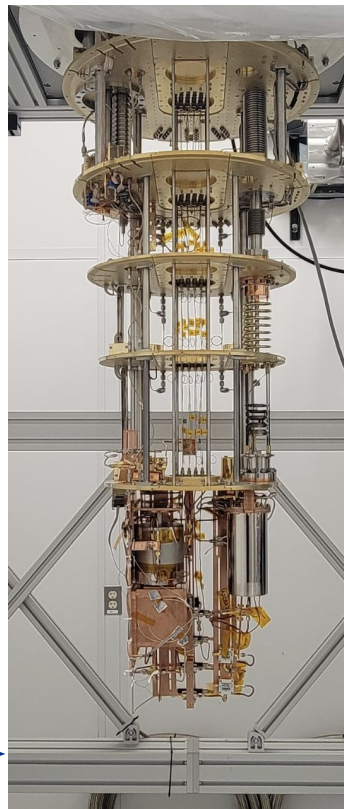
We plan to fabricate and operate prototype devices over the next year between UChicago, Northwestern, and Fermilab.

Hard problems in fab:

- How do you maximize your piezoelectric couplings, g_{nm} ?
- How do you keep qubit T_1 high when coupled to stray phonon modes?
- Can you engineer downconversion and couple 2Δ phonons into hBAR mode?

Testing goals:

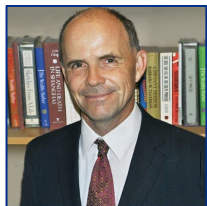
- Proof-of-principle tests within FNAL/UChicago surface labs
- Radioactive source and/or optical calibrations
- Low-background environmental runs (QUIET@FNAL).



Conclusions

We've found that the qubit-coupled hBAR is a promising QIS technology for single-phonon sensing

- Probes $O(10\mu\text{eV})$ acoustic phonons
- Fundamentally not reliant on pairbreaking!
- Sensitivity study here: <https://arxiv.org/abs/2410.17308>
- Will be experimentally exploring its promise as a low-threshold sensor in near future



Andrew
Cleland,
UChicago



Paolo
Privitera,
UChicago



Chris
Conner,
UChicago



Tongyan
Lin,
UCSD



Mukul
Sholapurkar,
UCSD



Sohitri
Ghosh,
FNAL



Dan
Baxter,
FNAL+NU



Enectali
Figueroa-F
eliciano,
NU+FNAL



Rakshya
Khatiwada,
IIT+FNAL



Tanner
Trickle,
FNAL



Ryan
Linehan,
FNAL



Thank you!

FERMILAB-SLIDES-24-0313-PPD

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Backup

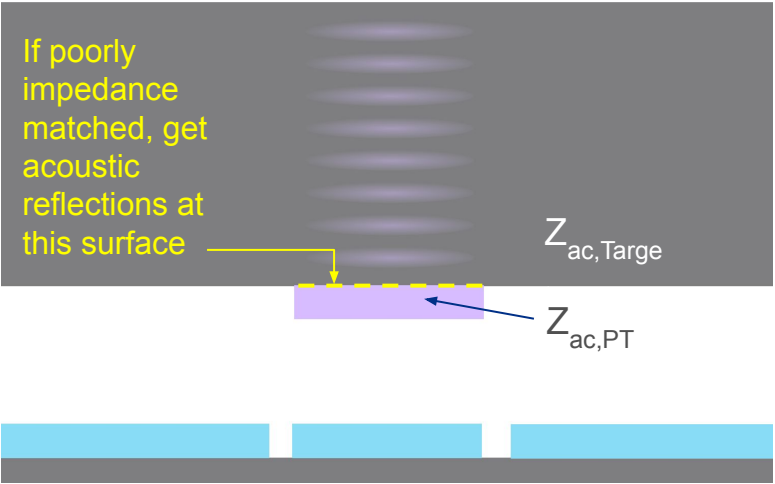
Acoustic Matching

Good acoustic impedance matching between the target chip and the piezoelectric is a “hidden” requirement in achieving good swap efficiency.

Acoustic impedance: density x sound speed

$$Z_{ac} = \rho c$$

Goal: match these parameters between the piezo and the substrate



Material	AlN	LiNbO ₃	GaN	Al ₂ O ₃	SiC	Si
ρ (kg/m ³)	3260	4600	6100	3.98	3210	2330
C (km/s)	11.3	6.5-7.3	3.96-8.0 (link)	11.25 (c-plane)	13.0	8.433
Z_{ac} (kg/m ² s)	37e3	29.3e3 – 33.6e3	24.0e4 – 48.8e3	44.7e3	41.7e3	19.6e3

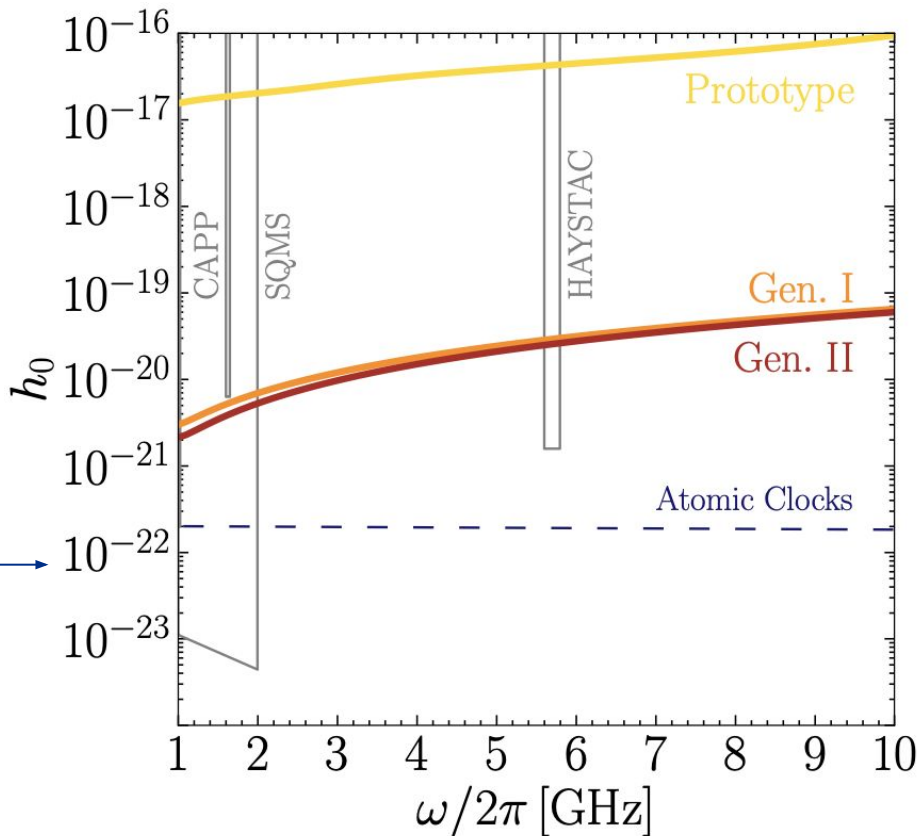
Gravitational Waves

High-frequency ($\sim$ GHz) gravitational waves possible to probe with qc-hBAR

- Quantum version of Weber Bars

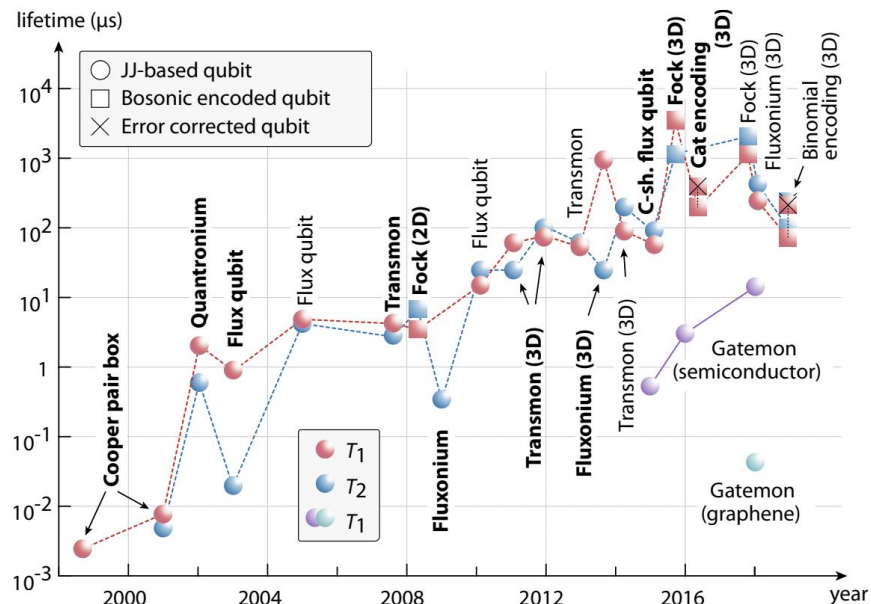
$$\begin{aligned}\delta H &= \frac{1}{2} \int d^3\mathbf{x} \rho_h \ddot{h}^{ij}(\mathbf{x}, t) \mathbf{x}^i \mathbf{x}^j \\ &\approx -\frac{\omega^2 \rho_h e_{\text{GW}}^{zz}}{2} h_0 \cos(\omega t) \int z u d^3\mathbf{x}\end{aligned}$$

- Here, assuming monochromatic source with amplitude h_0 , operating for 1 year $\longrightarrow$
- Many GW sources also transient ($\sim$ 30 seconds), but have larger strain amplitude than stochastic cosmological source



T_1 Time Evolution over the Last Two Decades

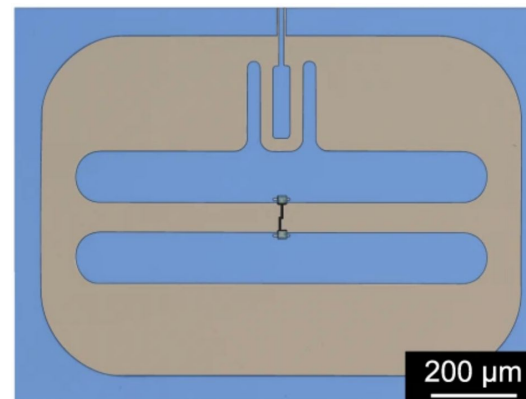
Rapid progress has been made in increasing coherence times in the last 20 years. Continued progress not guaranteed, but track record warrants optimism.



Source: Kjaergaard et al., "Superconducting Qubits: Current State of Play,"

<https://doi.org/10.48550/arXiv.1905.13641>

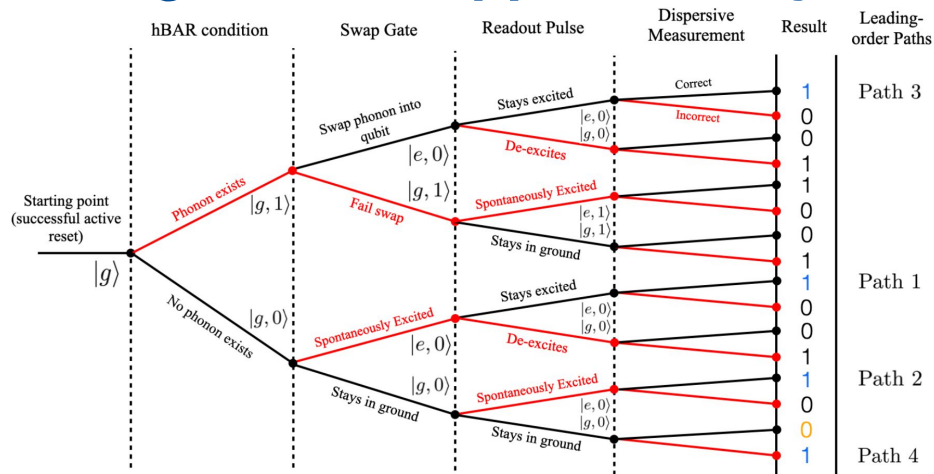
Recent Ta-based planar transmons pushing up into the many-100's of μs regime!



New material platform for superconducting transmon qubits with coherence times exceeding 0.3 milliseconds

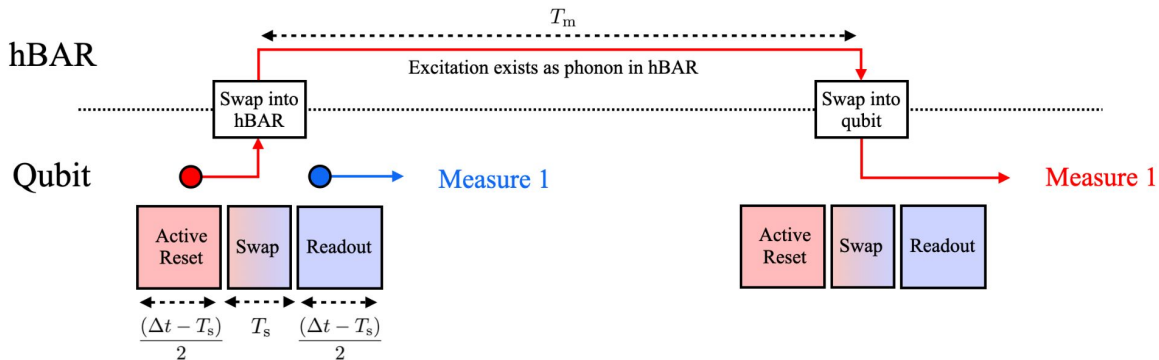
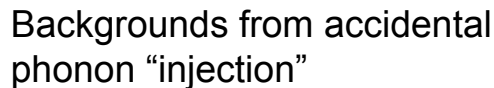
Alexander P. M. Place, Lila V. H. Rodgers, Pranav Mundada, Basil M. Smitham, Mattias Fitzpatrick, Zhaoqi Leng, Anjali Premkumar, Jacob Bryon, Andrei Vrajitoarea, Sara Sussman, Guangming Cheng, Trisha Madhavan, Harshvardhan K. Babla, Xuan Hoang Le, Youqi Gang, Berthold Jäck, András Gyenis, Nan Yao, Robert J. Cava, Nathalie P. de Leon & Andrew A. Houck

Backgrounds Supplementary

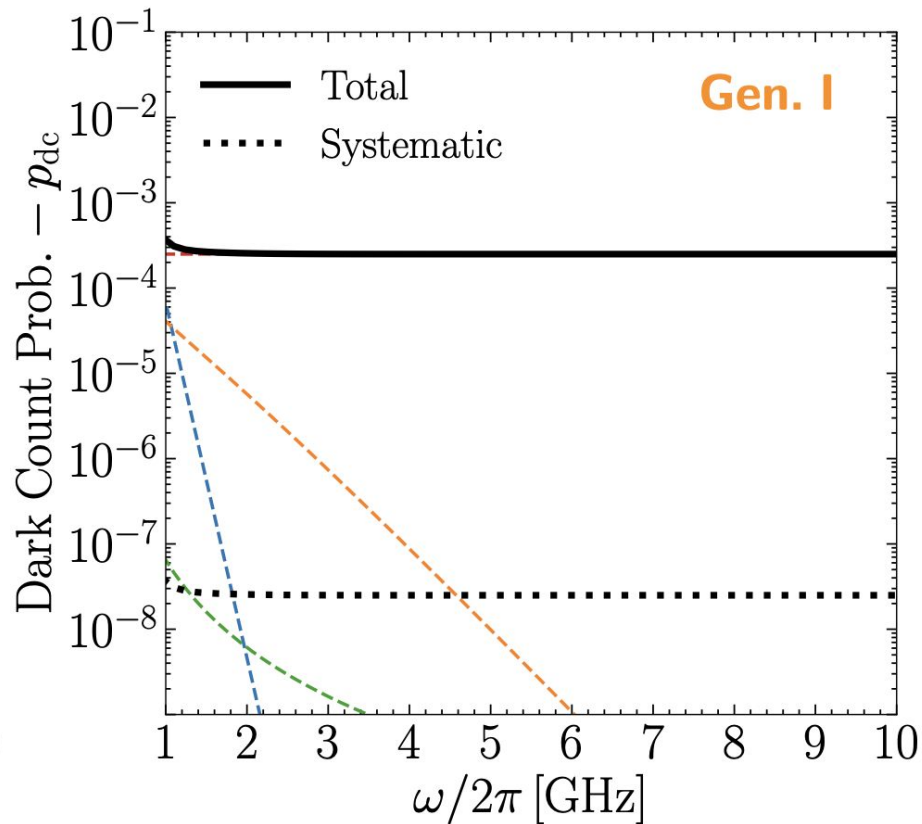
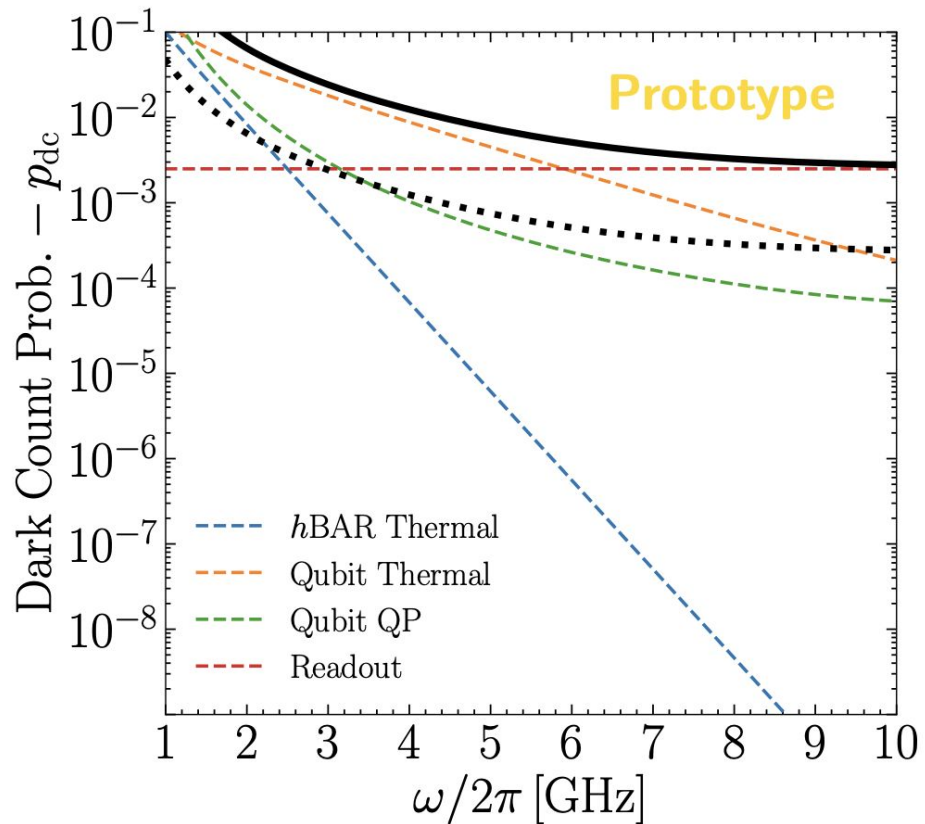


Construction of a background model:

- Built from a tree of various outcomes during a measurement
- Dominated by terms with only a single “small” probability



Backgrounds: Future Projections



Prototype/Gen-I/Gen-II

Prototype: “demonstrated in today’s devices”

Gen. I: Optimization + Background reduced

Gen. II: Scaled/multiplexed Gen. I

			Development Stage		
			Prototype	Gen. I	Gen. II
<i>h</i>BAR	PT Height	h	$0.8\,\mu\text{m}$	—	—
	PT Piezoelectric Coeff.	e_{pt}	$0.39\,\text{N/m/V}$	—	—
	Sound Speeds (T, L)	(c_t, c_l)	$(6, 11)\,\text{km/s}$	—	—
	Phonon Quality Factor	Q_{p}	10^6	—	—
	PT Radius	R	$100\,\mu\text{m}$	$400\,\mu\text{m}$	—
	Height	L	$400\,\mu\text{m}$	$40\,\mu\text{m}$	—
	Multiplicity	N_h	1	—	10^3
Qubit	Frequency Range	$(\omega_q^{\text{min}}, \omega_q^{\text{max}})/2\pi$	$(1, 10)\,\text{GHz}$	—	—
	Electric Field at PT	E_q	$2.9 \times 10^{-2}\,\text{V/m}$	—	—
	Qubit Quality Factor	Q_q	2.8×10^5	2.8×10^7	—
Background	Qubit Energy Gap	Δ	$176\,\mu\text{eV}$	—	—
	Normalized QP Density	x_{qp}	10^{-6}	10^{-9}	—
	<i>h</i> BAR Temp.	T_h	20 mK	5 mK	—
	Effective Qubit Temp.	T_q^{eff}	60 mK	20 mK	—
	Single Shot Fidelity	$\mathcal{F}$	$1 - 5 \times 10^{-3}$	$1 - 5 \times 10^{-4}$	—
	Sys. p_{dc} Fluctuation	$\delta p_{\text{dc}}/p_{\text{dc}}$	10^{-1}	10^{-4}	—.

TABLE I. Experimental parameters for the qubit-coupled *h*BAR (qc-*h*BAR) detector at different stages of development (“Prototype”, “Gen. I”, and “Gen. II”) assuming an *h*BAR composed of an Al₂O₃ chip and AlN PT, and an Al qubit. Entries with dashes assume the same value as in the preceding column. Generally, parameters in the Prototype column have been demonstrated today, those for Gen. I are projections for a device optimized for a new physics search, and Gen. II is composed of N_h Gen. I detectors operating simultaneously. Detailed discussion of the background parameters can be found in Sec. III B.

“Non-differential” readout scheme

- Individual cycles yield bernoulli variable Q_i , corresponding to qubit state
- Can form a test-statistic from sum:

$$\chi_{\text{non-diff.}} = \frac{1}{N} \sum_{i=1}^N Q_i$$

- Evaluate separation between S+B mean and B-only mean, in B-only std-dev.

$$p_{\text{s,non-diff.}}^{\text{thr}} \simeq \frac{n_{\sigma}}{\varepsilon_{\text{s}}} \sqrt{\frac{p_{\text{dc}}}{N}}$$

- Above is only true if systematic effects (variation in p_{dc}) can be removed with, say daily modulation

“Differential” readout scheme

- Take “target” and “sideband” measurements to get $Q_{i,1}$ and $Q_{i,2}$
- Can form a test-statistic from sum:

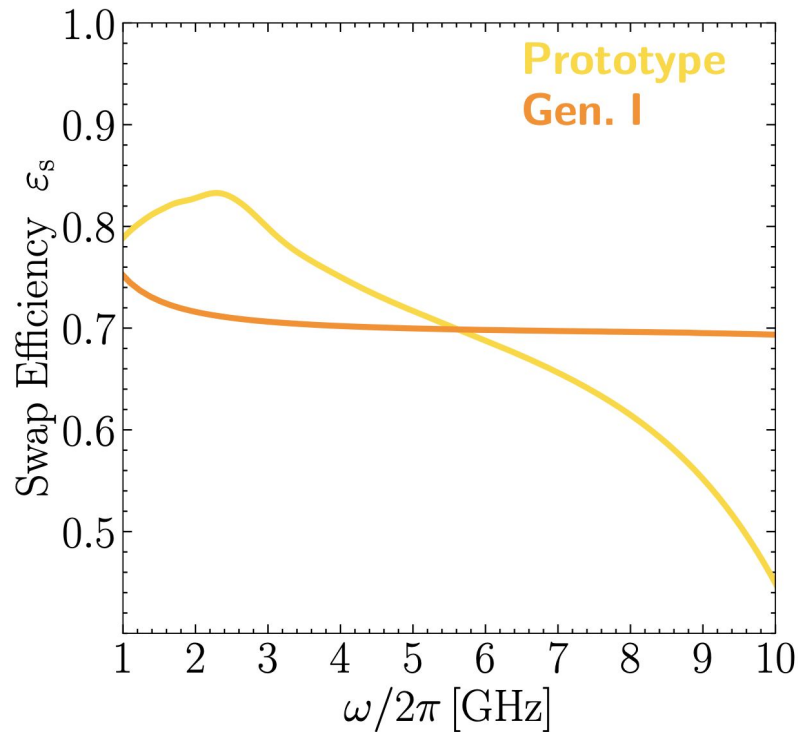
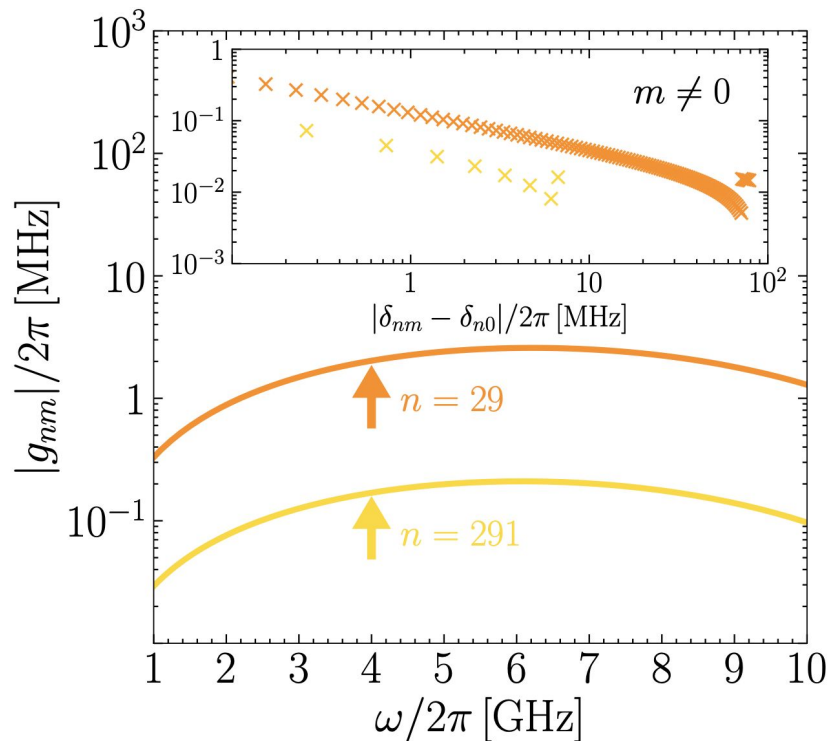
$$\chi_{\text{diff.}} = \frac{1}{N} \sum_{i=1}^N [Q_{i,1} - Q_{i,2}]$$

- Evaluate separation between S+B mean and B-only mean, in B-only std-dev.

$$p_{\text{s,diff.}}^{\text{thr}} \simeq \frac{n_{\sigma}}{\varepsilon_{\text{s}}} \left(\sqrt{\frac{2p_{\text{dc}}}{N}} + \delta p_{\text{dc}} \right)$$

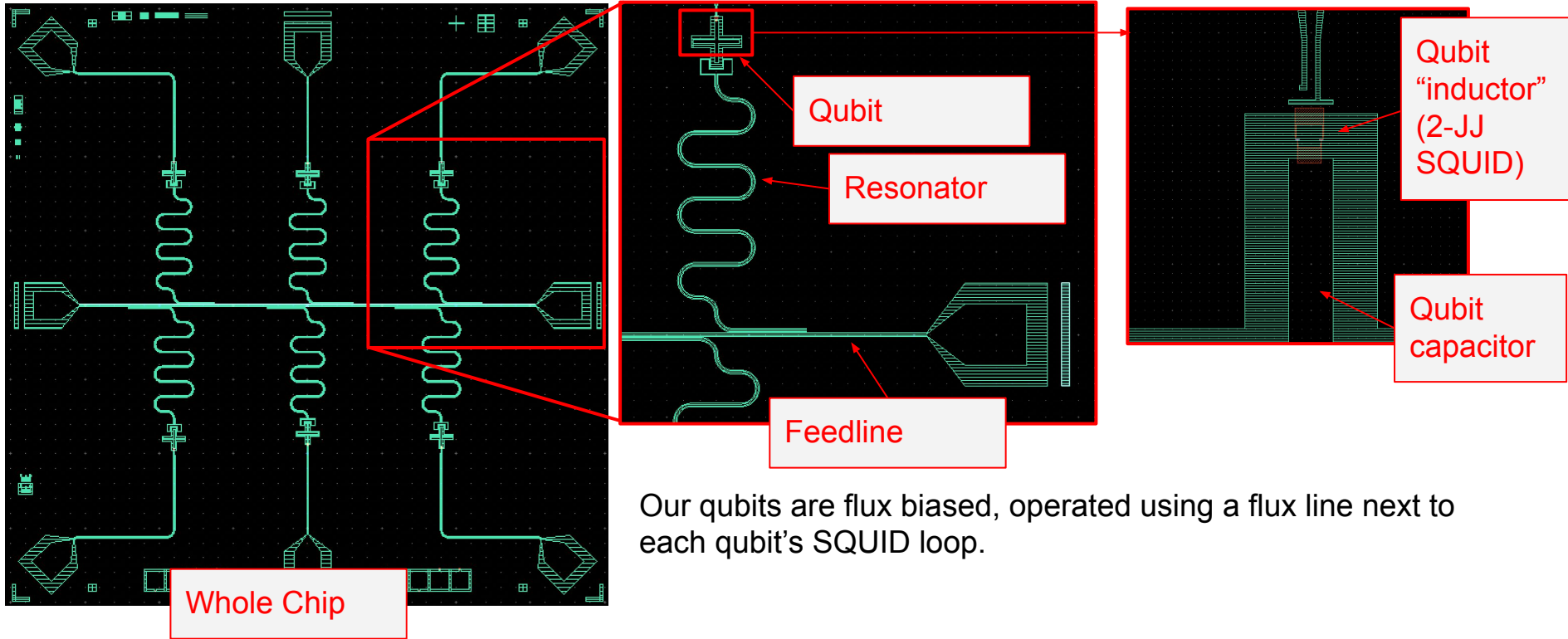
- Susceptible to variation in p_{dc} on time/frequency scales within a **pair** of measurements

Swap Efficiencies and Couplings



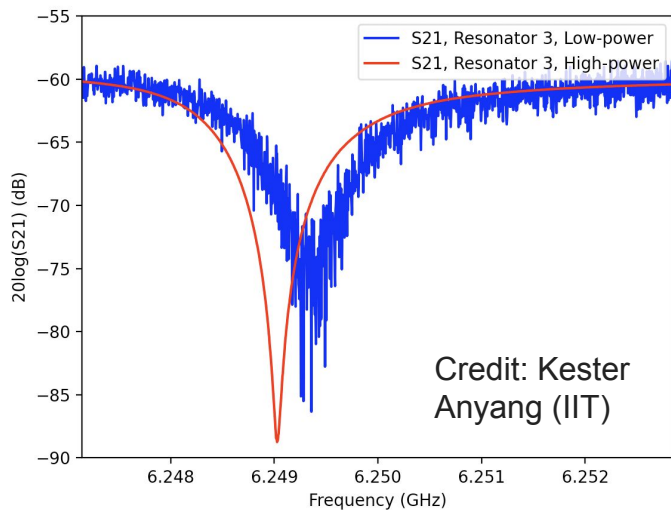
Device Design/Operation

Qubits read out using coplanar waveguide resonators coupled to a shared RF feedline.



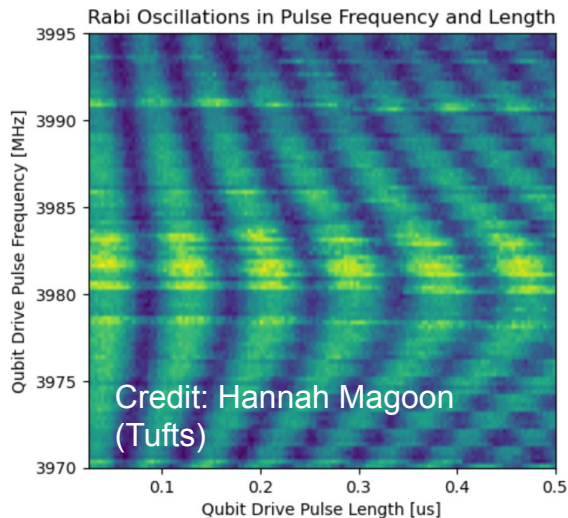
Qubit Bring-Up Tests

One-tone resonator spectroscopy (“punch-out”)



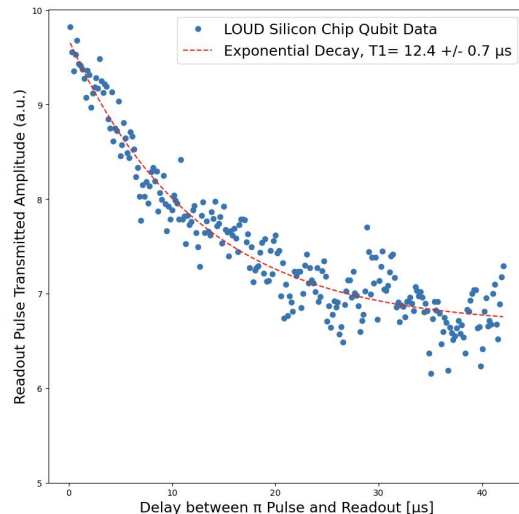
Purpose: determine that the qubit (i.e. the Josephson Junction) is “alive”, i.e. not burned out

Qubit spectroscopy + Rabi Oscillations



Purpose: find the qubit excitation frequency and calibrate a $|0\rangle \rightarrow |1\rangle$ pulse

T1 Relaxation Time



Purpose: Probe qubit decoherence times